HCCI Combustion: the Sources of Emissions at Low Loads and the Effects of GDI Fuel Injection

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Introduction

- HCCI engines are a low-emissions alternative to diesel engines.
  - Provide diesel-like or higher efficiencies.
  - Very low engine-out NO_X and PM emissions.

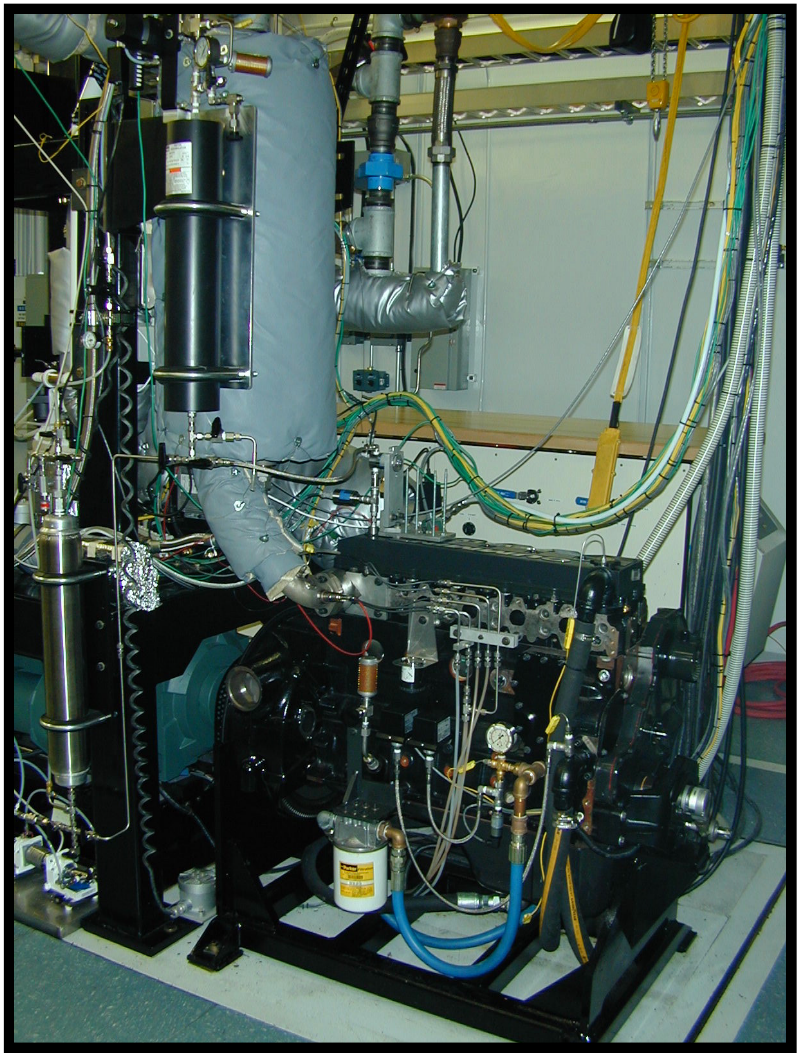
- Research is required in many areas to resolve technical barriers to the development of HCCI engines by industry.
  - The objective of our work is to help provide this understanding.

- Establish a laboratory to investigate HCCI combustion fundamentals.
  - <u>All-metal engine</u>: fully operational – result are subject of presentation.
  - <u>Optically accessible engine</u>: examine in-cylinder processes (end of 02).

- CHEMKIN kinetic-rate computations
  - Guide experiments
  - Assist in data analysis
  - Show limiting behavior

Engine and Operating Conditions

HCCI All-Metal Engine

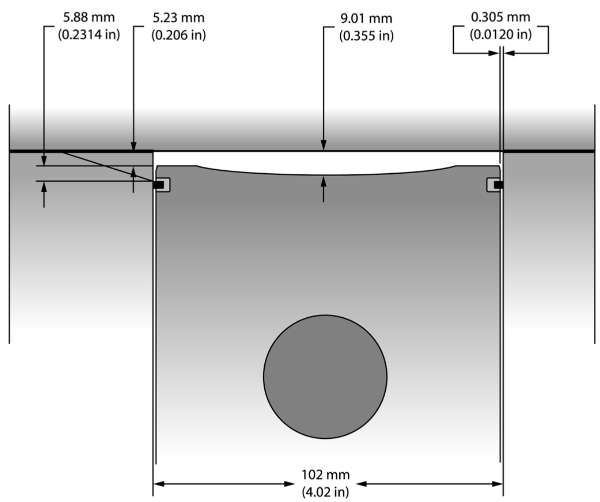


Based on Cummins B, 0.98 ltr./cyl.

- Six-cylinder diesel engine converted for balanced, single-cyl., HCCI operation.
- Versatile facility to investigate various operational and control strategies.
  - Compression ratios from 13 - 21 (18)*
  - Swirl ratios from 0.9 - 3.2; 7.2 (0.9)*
  - Speeds to 3600 rpm (600 - 1800 rpm)*
  - Multiple fueling systems.
    - > Fully premixed (curr.)*
    - > Port fuel injection (PFI)
    - > Direct injection, gasoline-type (curr.)*
    - > Direct injection, diesel-type
  - Liquid or gas-phase fuels (iso-octane)*
- Complete intake charge conditioning.
  - Intake temperatures to 180° C. (varies)*
  - Intake pressures to 4 bars. (varies)*
  - Simulated or real EGR. (none)*

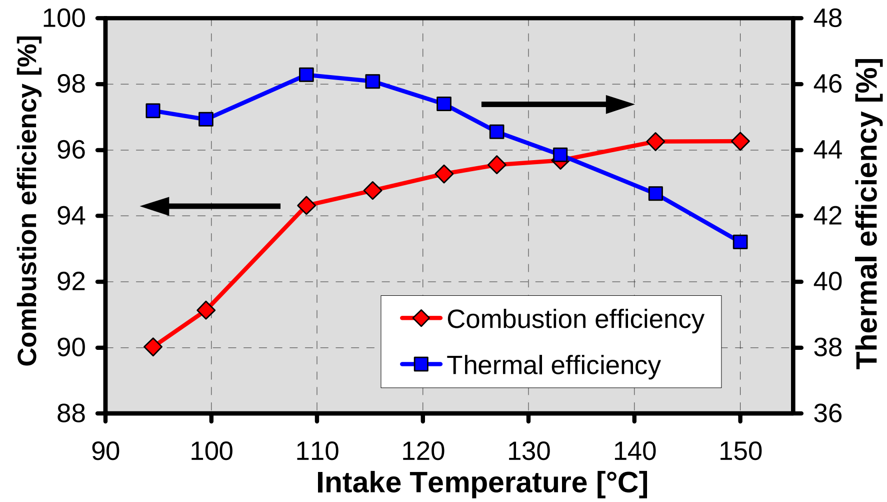
* Values in (red) are used for current work.

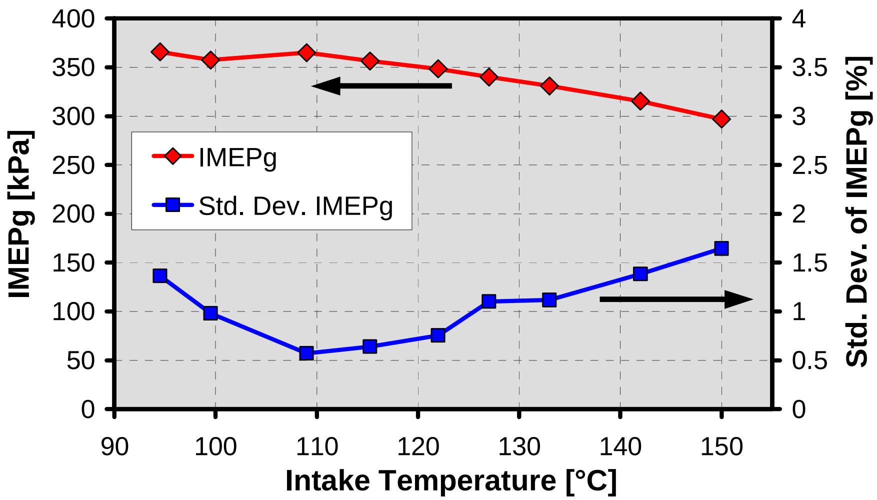
Engine Appears to be Working Well

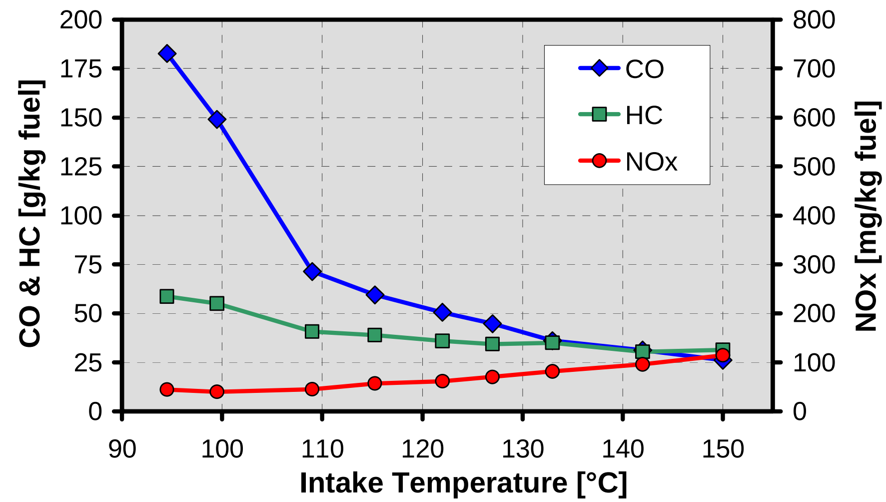


- Large squish clearance.
- Ring-land crevice 1% of TDC vol.
- Various compression ratios

CR = 18; ϕ = 0.24; P_{in} = 120 kPa; 1200 rpm; Well-Mixed Charge





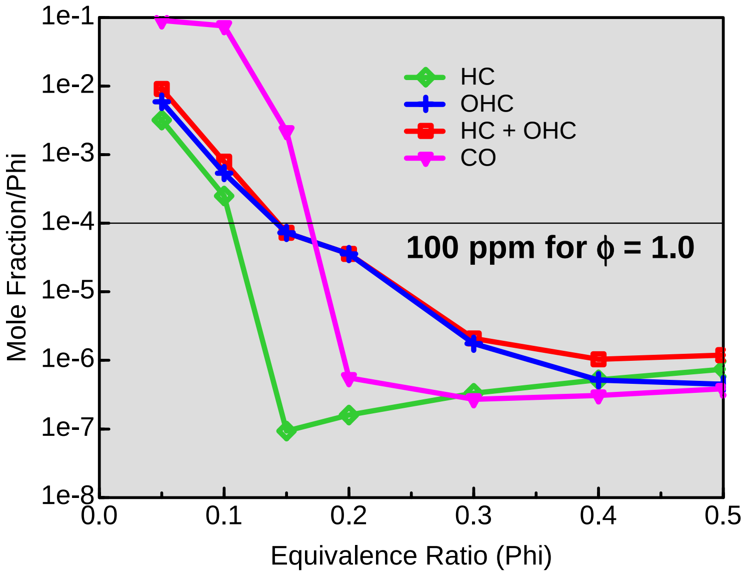


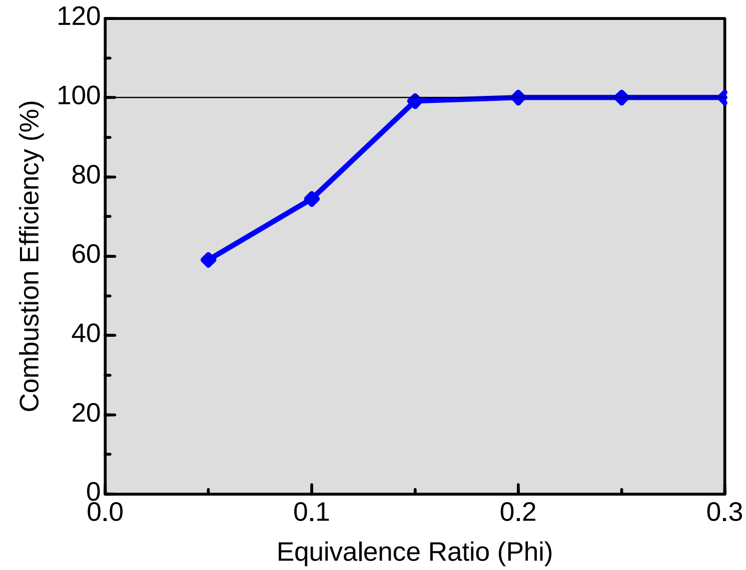
Computational Approach

- Senkin application of the CHEMKIN-III kinetics rate code.
  - Single-zone model with uniform properties and no heat transfer.
  - Allows compression and expansion with slider-crank relationship.
  - Full chemistry for iso-octane (Westbrook *et al.*, LLNL).
- Great oversimplification of a real engine. Model cannot reproduce all real-engine behavior.
- Model is well suited for investigating certain fundamental aspects of HCCI combustion.
  - Allows the effects of kinetics and thermodynamics to be isolated and evaluated without complexities of walls, crevices, and inhomogeneities.
    - > Assists in analysis of experimental data by separating chemical-kinetic and physical effects.
  - Represents the adiabatic limit for bulk-gas behavior in real engines.
  - Guide experiments by showing approximate trends in ignition timing & temperature compensation with changes in operating conditions.

CHEMKIN predicts incomplete bulk-gas reactions at low loads.

Iso-Octane; 1800 rpm; CR = 21; T_{in} = 380 K; P_{in} = 1 atm.





- Below ϕ = 0.2, emissions rise followed by a drop in combustion efficiency.
  - Temperatures are too low to complete reactions, especially CO $\rightarrow$ CO_2.
- Indicates high emissions of OHC as well as CO and HC.
  - OHC not well-detected by standard FID HC detector, and they can be harmful.
- Results for bulk-gas alone, in the absence of heat transfer.
  - Occurs in range of interest (typical diesel idle conditions are ϕ = 0.10 - 0.12).
  - In real engine, heat transfer will shift onset of incomplete reactions to higher ϕ.
  - Walls & crevices also add to emissions.

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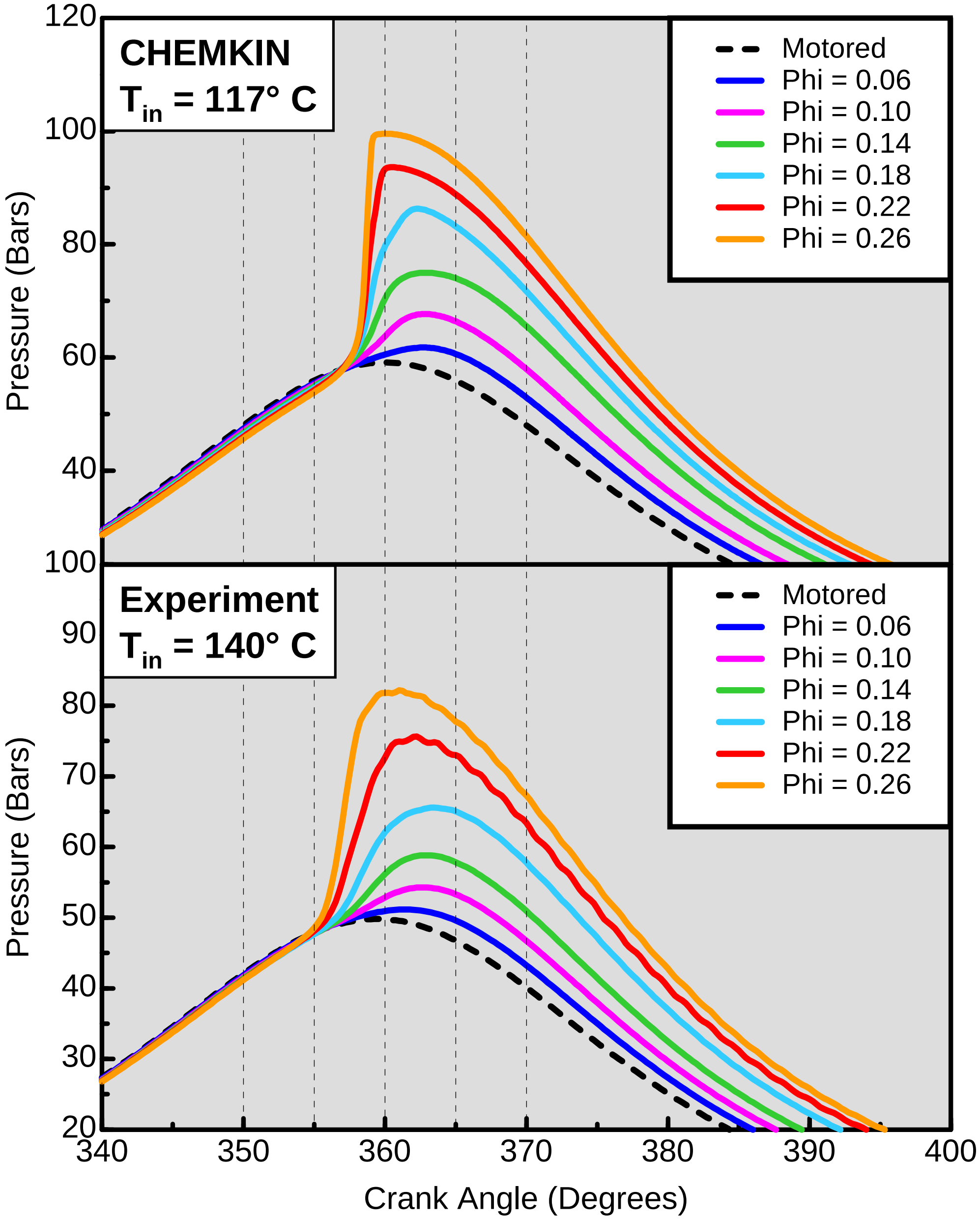
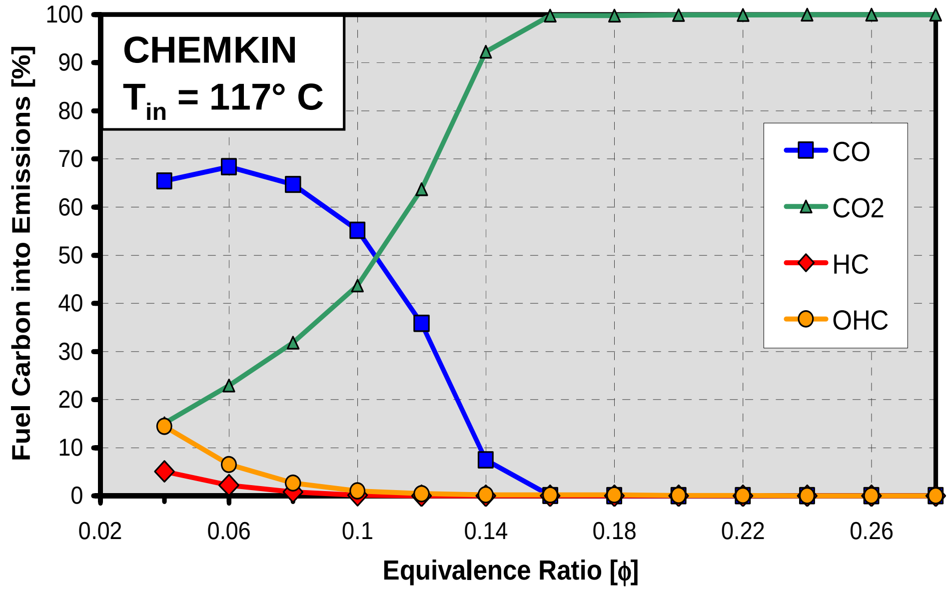
Vary ϕ: Experiment and CHEMKIN

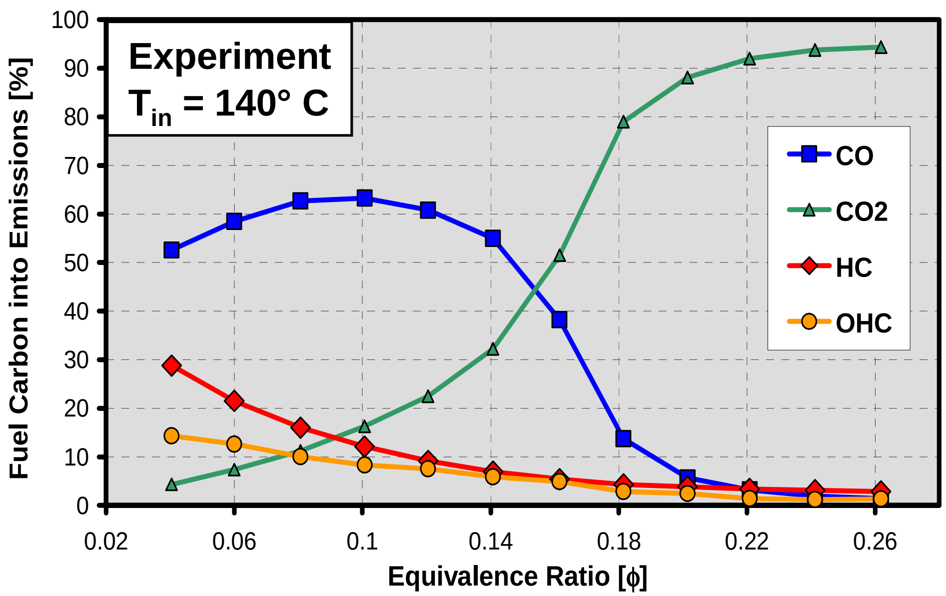


Iso-Octane ; CR = 18; 1200 rpm; P_{in} = 120 kPa; Pre-Mixed

- Intake temperature adjusted for 50% burn at TDC for ϕ = 0.14.
  - Experiment: T_{in} = 140° C
  - CHEMKIN: T_{in} = 117° C
- Experiment shows greater variation in combustion phasing.
  - Heat transfer and residuals.
  - Advanced timing at higher loads has little effect on emissions.
  - Timing retard at low loads is small and has little effect on emissions.

Emissions: Experiment and CHEMKIN

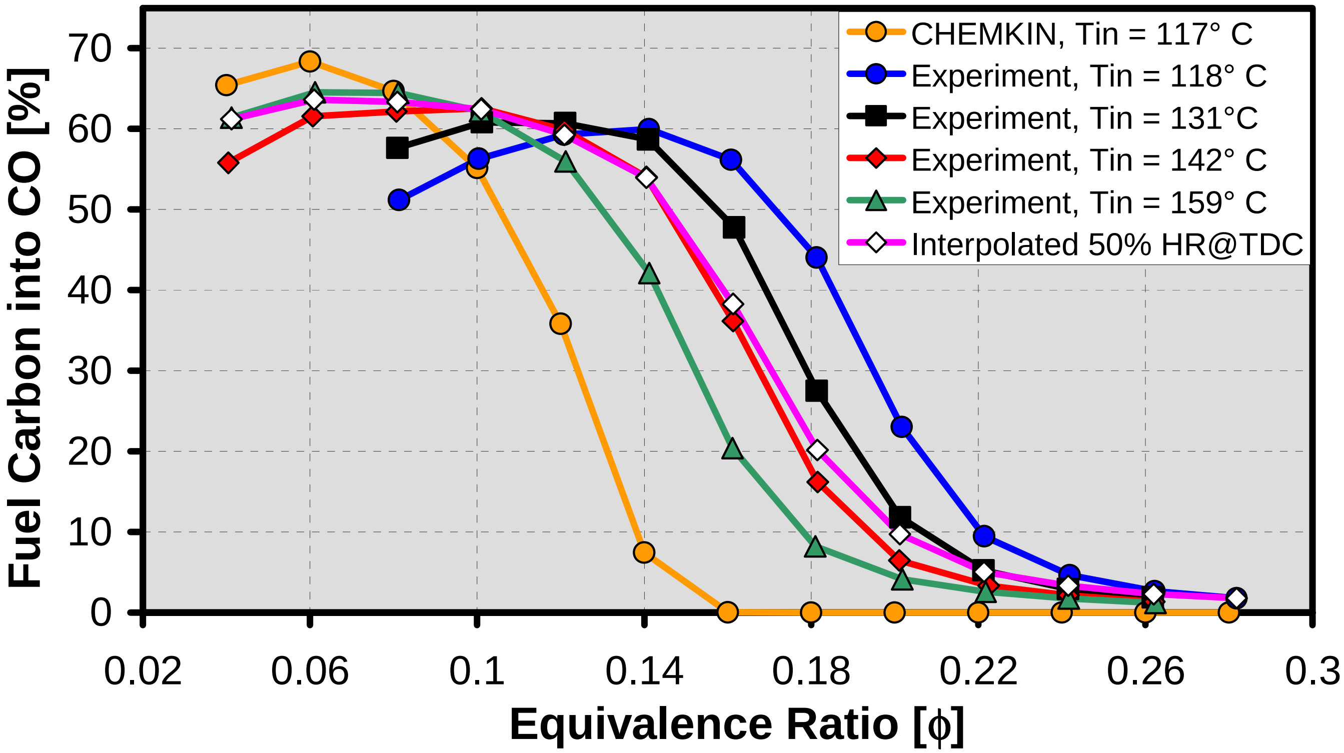




1200 rpm; CR = 18; P_{in} = 120 kPa; Pre-Mixed Fueling

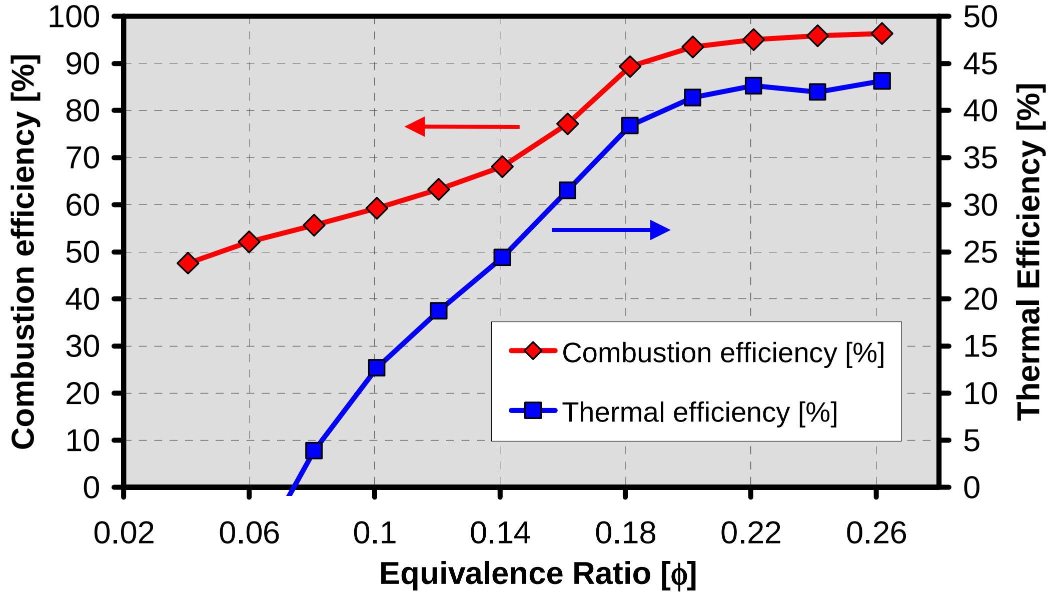
- Experimental T_{in} was increased to maintain near-TDC ignition.
  - Compensate for heat transfer.
- Experimental emissions match model closely.
  - CO levels match closely ~65%
    - > Bulk-gas source.
  - HC, rise for $\phi < 0.2$ is similar to model indicates bulk-gas source at low ϕ.
    - > Near-constant baseline level for $\phi > 0.2$ suggest crevice source.
  - "Missing carbon" in experiment indicates presence of OHCs.
    - > Similar to model, but lower due to FID response.

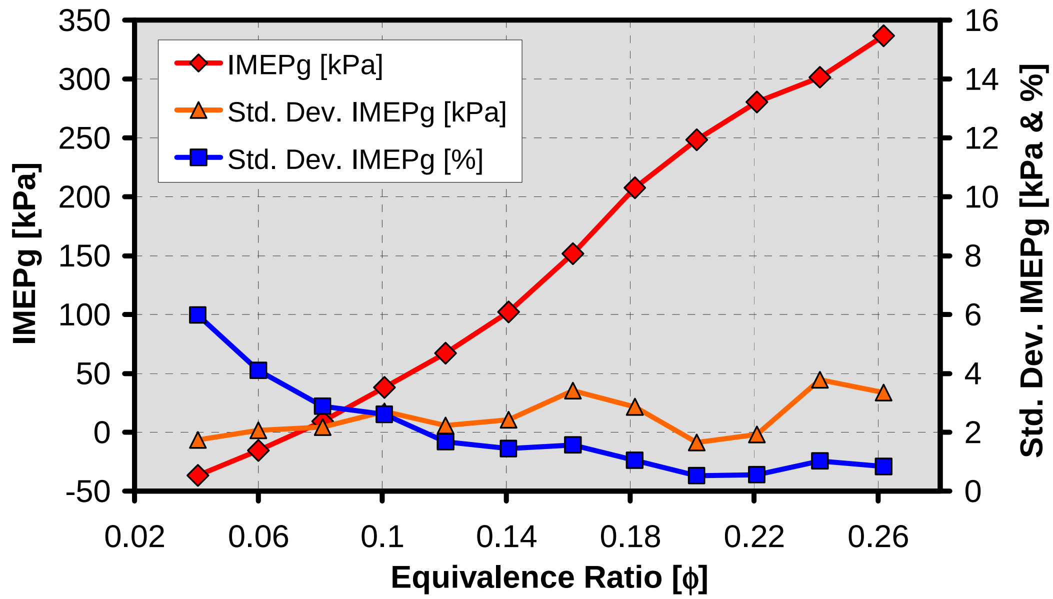
Comparison of CO Emissions with ϕ at Various T_{in}



- Magnitude of increase in CO with decreasing ϕ agrees well with the CHEMKIN results. Shows incomplete bulk-gas reactions are the cause.
  - Onset of rise in CO levels is shifted to higher ϕ in engine due to heat transfer.
  - Rise in CO shifts to progressively higher ϕ as T_{in} is reduced (lower $T_{combustion.}$).
  - Engine data also show a large drop in combustion efficiency at low loads, corresponding to the increase in CO.

Efficiencies and Combustion Stability

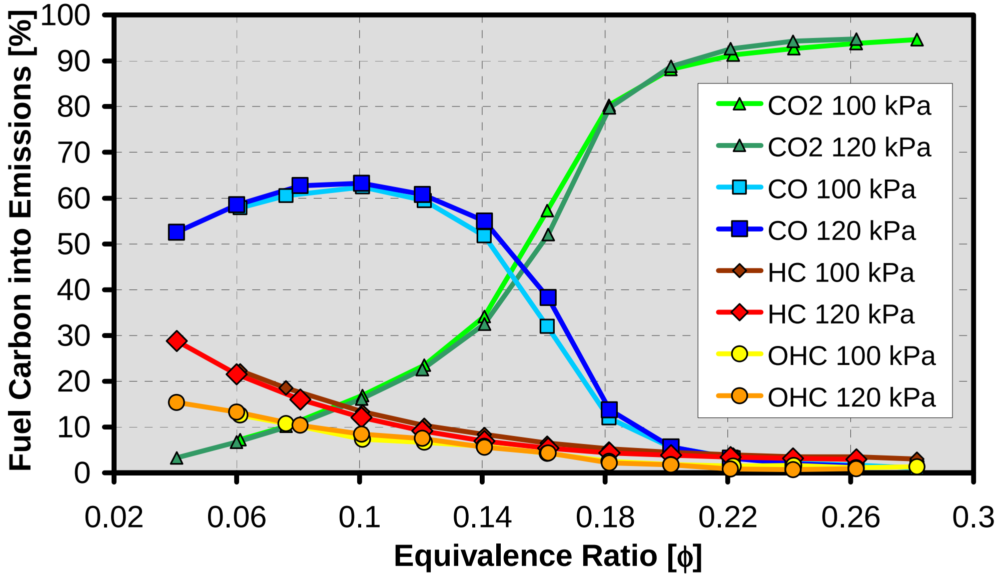


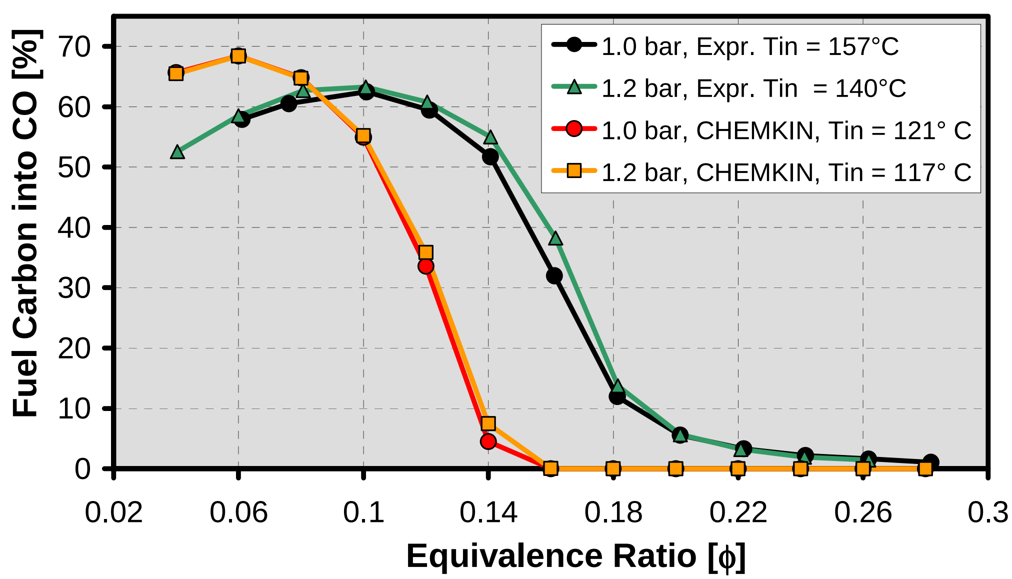


CR = 18; P_{in} = 120 kPa; T_{in} = 140° C; Pre-Mixed

- Combustion efficiency drops from 95% to 60% as fuel is reduced to low-idle, ϕ = 0.1.
  - Similar drop in pressure-indicated thermal efficiency.
  - Commensurate with the rapid rise in CO.
- Std. Dev. of IMEP is 2 – 4 kPa for all fueling rates (ϕ).
  - Increase at ϕ = 0.16 due this being in the middle of the rapid rise in CO.
- Normalized σIMEP increases below ϕ = 0.1 because IMEP is near zero.
  - Std. Dev. of IMEPg $\leq$ 2.6% from ϕ = 0.1 to ϕ = 0.26.

Effect of Intake Pressure

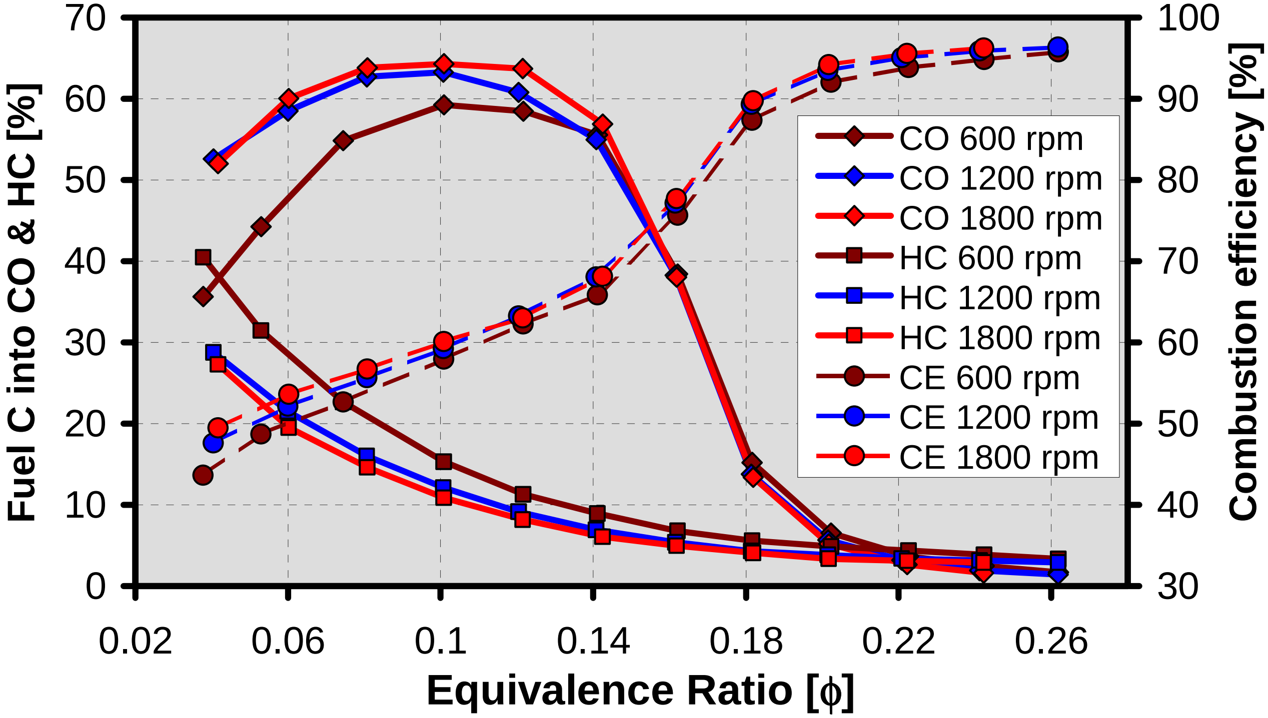




1200 rpm; CR = 18; Pre-Mixed

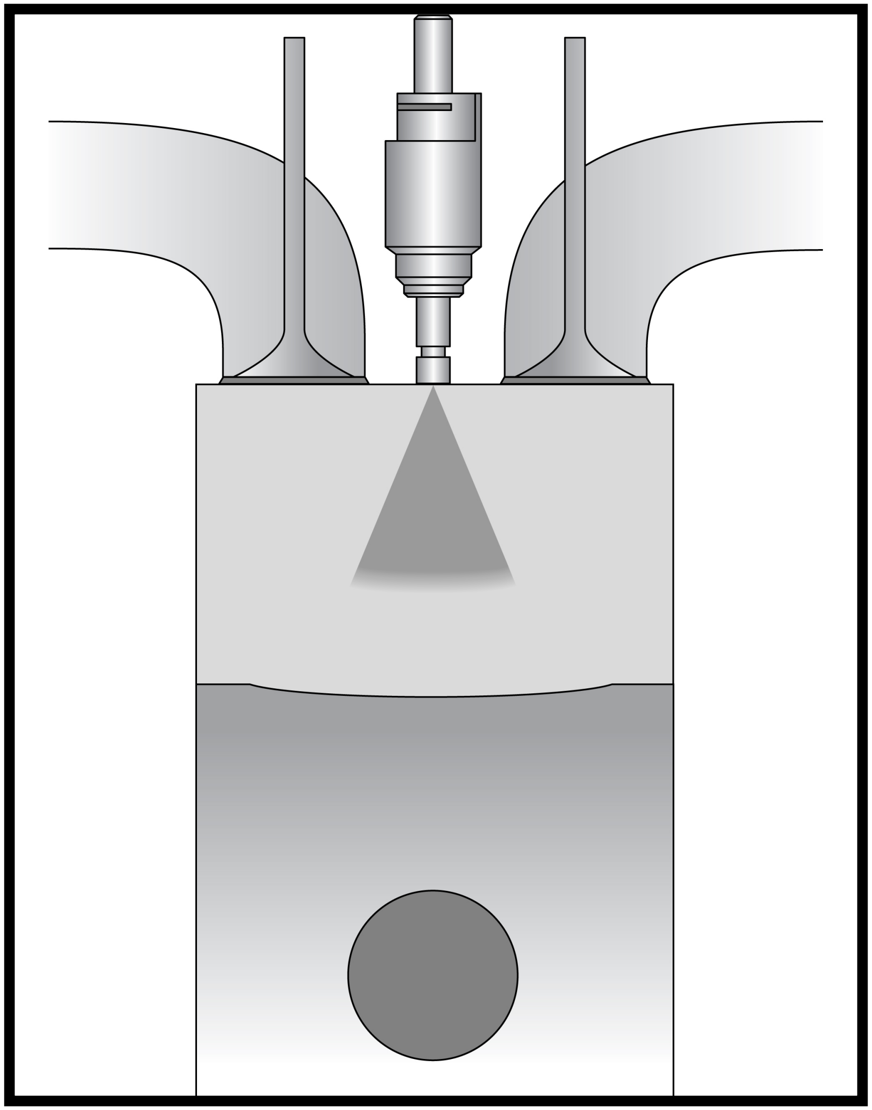
- Changing P_{in} from 101 to 120 kPa has little effect on onset of incomplete bulk-gas reactions when combustion phasing is maintained.
  - Experiment and CHEMKIN both show slightly lower CO values during rapid rise.
- T_{in} adjusted for 50% burn at TDC for $\phi = 0.14$.
  - 101 kPa: T_{in} = 157° C
  - 120 kPa: T_{in} = 140° C

Effect of Engine Speed on Bulk-Gas Reactions



- T_{in} adjusted to maintain combustion phasing at TDC for $\phi = 0.14$.
  - Higher compression temperatures compensate for reduced time for reactions.
- Engine speed has little effect on the fueling rate at which the onset of incomplete bulk-gas reactions occurs – for iso-octane.
  - In agreement with CHEMKIN computations.
- Results suggest that special combustion strategies will be required for low-load operation.

GDI Fueling: Vary Injection Timing



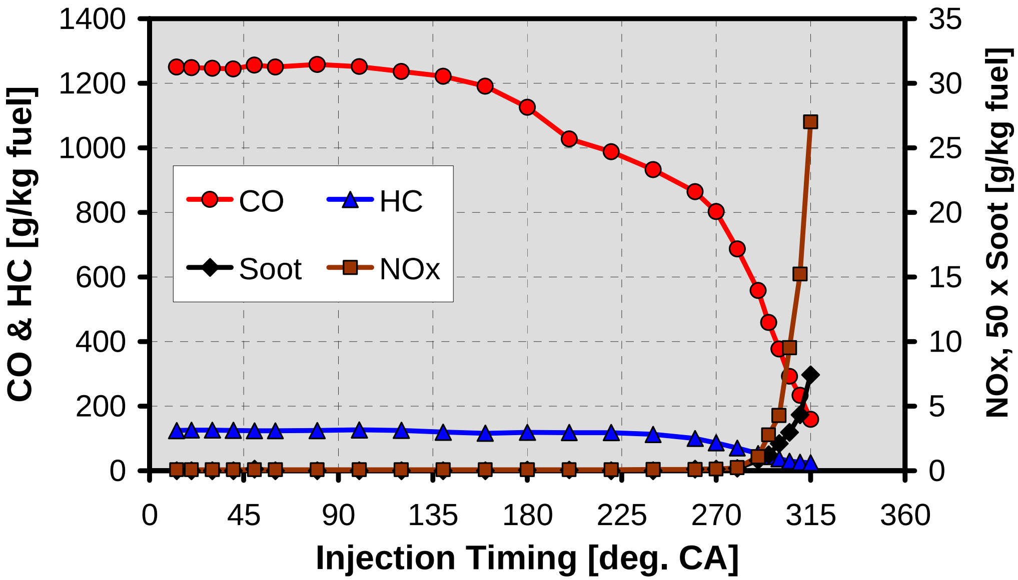
Early Injection

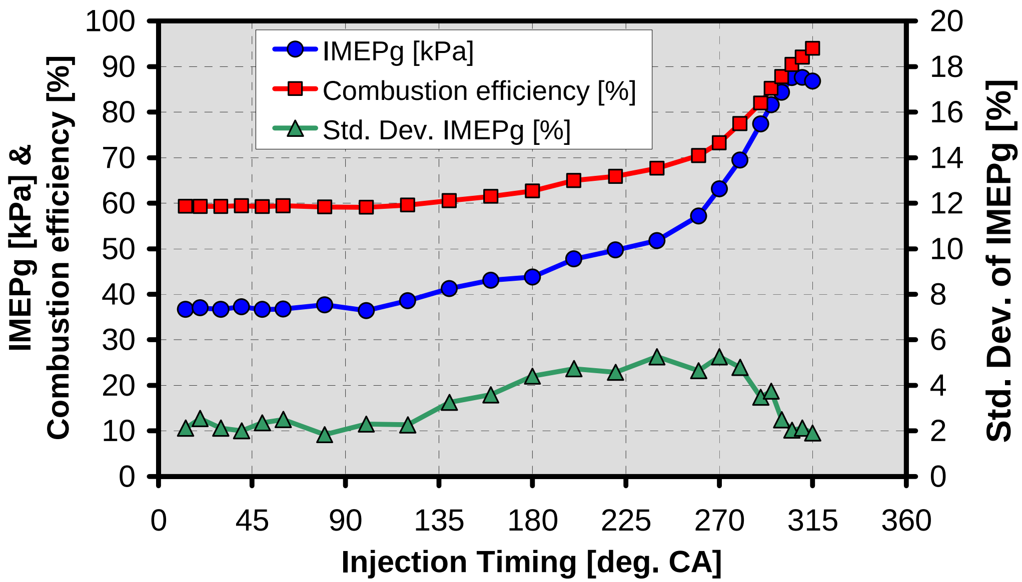
- Provides a fairly uniform mixture.
  - Can lead to incomplete bulk-gas reactions at low loads, as predicted by CHEMKIN.

Late Injection

- Can provide partial charge stratification.
  - Mixture locally richer for the same fueling rate.
  - Offers the potential to mitigate incomplete bulk-gas reactions at light loads.
- Also, could prevent fuel from reaching ring-land crevice.
  - Reduce baseline emissions.

Variation in Injection Timing: ϕ = 0.1





T_{in} = 142° C; P_{in} = 120 kPa; 1200 rpm; GDI fueling

- Early injection (0-90° aTDC intake) provides a well-mixed charge.
  - High CO and low combustion efficiency for ϕ = 0.1.
- Retarding injection improves combustion and emissions for low-load operation.
  - Injection at 290° reduces CO and HC emission substantially with only about 1g/kg-fuel NO_X (4 ppm).
  - Combustion efficiency increases from 59% to 82%.
- Further improvements possible with optimized stratification.

Summary and Conclusions - 1

- Metal HCCI research engine appears to be functioning well.
  - At fully combusting conditions: $\eta_{thermal}$ ~ 46%, σIMEP < 1%, CO < 65 g/kg (1000 ppm), HC < 35 g/kg (1200 ppm), NO_X ~ 0.06 g/kg (1 ppm).

- CHEMKIN results show that for fuel loads below ϕ ~ 0.16, bulk-gas reactions are incomplete, even for an idealized adiabatic engine.
  - Significant combustion inefficiencies, very high CO, and increased HC.
    - Temperatures are too low to complete reactions, mainly $CO \rightarrow CO_2$.
  - Indicate that significant OHC emissions should occur. (OHC is ~2x HC).

- Experimental data show a very similar trend to the changes in emissions and combustion efficiency as fuel loading is reduced.
  - CO levels match very closely with those of the model (~65% of fuel C).
    - Bulk-gas must be the source.
  - Onset of incomplete bulk-gas reactions occurs at higher ϕ ~ 0.2 due to heat transfer cooling the charge.

Summary and Conclusions - 2

- The "missing carbon" in the emissions measurements matches the expected OHC trends.
  - HC detector (FID) has low sensitivity to OHC.
- Combustion stability was good even at idle loads, σIMEP $\leq$ 2.6%.
- Increasing P_{in} from 1.0 to 1.2 bars had little effect on the onset or magnitude of incomplete bulk-gas reactions when ignition timing was maintained.
- Changing speed from 600 to 1800 rpm has almost no effect on the onset or magnitude of incomplete bulk-gas reactions for iso-octane.
  - Increased compression temperatures required to maintain ignition timing compensate for reduced time to complete reactions.
- Partial charge stratification by late-cycle fuel injection appears to have a strong potential for mitigating the difficulties of low-load operation.